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S.H. Glick, F.J. Pern, D. Tomek, and J. Raaff
National Renewable Energy Laboratory

G.L. Watson
University of Colorado, Boulder

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National Renewable Energy Laboratory

1617 Cole Boulevard
Golden, Colorado 80401-3393

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Performance Degradation of Encapsulated Monocrystalline-Si Solar Cells upon Accelerated Weathering Exposures

S. H. Glick, F. J. Pern, G. L. Watson,* D. Tomek, J. Raaff

National Center for Photovoltaics (NCPV)

National Renewable Energy Lab (NREL)

1617 Cole Boulevard, Golden, CO 80401

* Currently at University of Colorado, Boulder, CO

ABSTRACT

We have performed accelerated exposures to study performance reliability and materials degradation of a total of forty-one 3-cm x 3-cm monocrystalline-Si (c-Si) solar cells that were variously encapsulated using accelerated weathering protocols in two weatherometers (WOMs), with and without front specimen water sprays. Laminated cells (EVA/c-Si/EVA, ethylene vinyl acetate) with one of five superstrate/substrate variations and other features including with and without: i) load resistance, ii) Al foil light masks, and iii) epoxy edge-sealing were studied. Three additional samples, omitting EVA, were exposed under a full-spectrum solar simulator, or heated in an oven, for comparison. After exposures, cell performance decreased irregularly, but to a relatively greater extent for samples exposed in WOM where light, heat, and humidity cycles were present (solar simulator or oven lacked such cycles). EVA laminates in the samples masked with aluminum (Al) foils were observed to retain moisture in WOM with water spray. Moisture effects caused substantial efficiency losses probably related in part to increasing series resistance.

1. Introduction

This work was the third in a series of accelerated test studies [1, 2]. High module efficiency, long service life (25 to 30 years), performance, and durability favorably impact PV system cost equations. Accelerated exposure and weather testing validate both module processing materials and methods, and pose the potential for reduced test times when compared to field deployment. The studies address these issues, especially concerns regarding stability of module materials.

2. Experimental

Three ethylene-vinyl acetate (EVA) formulations (commercial A9918 and 15295, and NREL-V11) were used to encapsulate c-Si cells with superstrate/substrate layers consisting of either borosilicate-glass/EVA/c-Si/EVA/glass or glass/EVA/c-Si/EVA/TPT. A third configuration of glass/c-Si/glass was made with no EVA in direct contact with the Si-cell. Some samples such as these were sealed using an epoxy on mechanically abraded glass-edges, to improve adhesion. Some samples were fitted with a 1-ohm load resistor, and some were wrapped in Al foil (see Table 1). Most of the samples, divided into two sets, were exposed separately in two Atlas Model Ci4000 WOMs using an accelerated weathering protocol with or without front

specimen water spray [3]. One set was exposed for 1400 MJ/m² and the other 650 MJ/m². Two glass/c-Si/glass-type samples were exposed under a full-spectrum solar simulator (FS-SS, ~6.5 UV suns) at 70°-75°C, and one was treated in an oven in the dark at 85°C.

Table 1. Sample Matrix, Configurations, IDs, and Exposures used in the Experiment.

Laminate Configuration	Sample ID, Exposure, and other details			
	WOM+S	Oven	FS-SS	WOM-S
G/A9918/G	1, 2, <u>f</u> [5], C			7, 9, <u>A</u>
G/15295/G	<u>f</u> [E], E, <u>M</u> , N			D, <u>L</u> , O
G/V11/G	<u>14</u> , <u>f</u> [15], <u>18</u> , 1A			<u>19</u> , 1C
G/A9918/TPT	3P, <u>3R</u>			3Q
G/15295/TPT	<u>3W</u> , C4			C5
G/V1/TPT	<u>4A</u> , C6			49
SOF/A9918/G	<u>2Q</u> , 2S			2O
SOF/15295/G	2U, <u>2W</u>			2Y
TFZL/A9918/G				5D, <u>5E</u>
No EVA Contact	<u>C9</u> , C10	C8	7H, 7K	7MA, C7
No. of Samples	24	1	2	17
Legends: Underlined ID# = Sample w/ 1-ohm resistor load f[ID#] = Sample wrapped in aluminum foil G = Borosilicate glass; SOF = Solarphire® glass. (all 1/8" thick) EVA = A9918, 15295, NREL-V11 formulated encapsulants TPT = Tedlar®/polyester/Tedlar® tri-laminate TFZL = Tefzel® (1.5 mil) No EVA Contact = c-Si cell not directly laminated with EVA				
Exposures: WOM+S: Atlas Ci4000 model, used "Accelerated Weathering Protocol" [3] with front specimen water spray. 1400MJ/m ² WOM-S: same as WOM+S but no water spray. 650MJ/m ² Oven: heated in the dark at 85°C. FS-SS: an ORIEL full spectrum solar simulator at 70°-75°C.				

3. Results and Discussion

In general, the results show cell efficiency decreased irregularly, as previously observed for cell samples exposed under solar simulators or in ovens [1, 2]. However, the extent of cell efficiency decrease is relatively greater for the samples exposed in the WOMs where cycles included light (~2.7 UV suns, over 300–400 nm broadband)/dark, hot/cool (~92°C/40°C), and low/high relative humidity (~30/95 %RH) conditions. The cell samples, *regardless* of encapsulation configuration and with or without epoxy edge

seal and 1-ohm load, show a random loss of efficiency from -2.3% to -61.5% after 1400 MJ/m² exposure in WOM with water spray, and from +0.4% to -49.2% after 650 MJ/m² exposure in WOM without water spray.

Browning of the EVA encapsulants occurred more and greater for A9918 than 15295, with a pattern spreading outward from the cell area. This pattern made it problematical to characterize EVA optical changes in laminate regions adjacent to cells using our usual UV-vis transmission or color-index scanning techniques. Quantum efficiency measurements overcame this impasse. UV-filtering, cerium oxide-containing Solarphire® superstrate glass reduced substantially EVA A9918 discoloration. Delamination of EVA from Si cell surfaces (front and back) was commonly observed, which also appeared as small bubbles observed more often in the glass/EVA/glass laminates. Cracking of the glass superstrate or substrate plates occurred on some samples during or in the later stage of WOM exposures.

Moisture ingress from edges of glass/glass and glass/TPT laminates or along the cracked glass regions appeared to cause visible degradation or corrosion of the Ag gridlines and PbSn(Cu) tab ribbons and a rusty appearance on many cells. Moisture retention by the EVA, manifest as turbidity in encapsulant polymers, was observed for the laminates wrapped in Al foils and treated in WOM with water spray. These same effects were not observed for unmasked samples otherwise similarly exposed and using the same materials. This suggests that light exposure exerts some driving force to move moisture out of the laminates, but heating/cooling and high humidity act oppositely. Moisture condensed into water was observed inside one glass/c-Si/glass sample (C10) edge-sealed with epoxy, resulting in extensive corrosion of the cell metalizations. Adhesion loss between epoxy and glass (crack observed) was the likely cause for this observation, yet this result nevertheless highlights the negative impacts moisture can exert on cell materials. Both moisture effects caused large efficiency losses on three cells (i.e., -39%, -54.8%, and -61.5%). In contrast, for the glass/c-Si/glass cells exposed to FS-SS at 70°-75°C in room relative humidity, efficiency losses were 0% and 1.8%; and -12.1% for the cell sample heated in an oven at 85°C.

Longer-term loss (>200 to 400 MJ/m²) in measured efficiency [Fig. 1] for many samples often correlated quite well with changes in series resistance (R_s), as derived from the resistance at maxV (far into forward bias, ~0.8V) from dark I-V curves [Fig. 2]. Results here suggest that for many samples in this study, loss in cell efficiency may at least in part be related to gradual increases in series resistance. The relation of moisture ingress to increasing series resistance should be further investigated. A consistent correlation between efficiency loss and shunt resistance (derived approximately from resistance at minV, minimum reverse bias, ~ -0.2V) was not always observed. This was speculatively attributed to lower signal-to-noise ratios in the small current values (measured in the reverse bias regions of the dark I-V curves) used to derive these resistance values at minV.

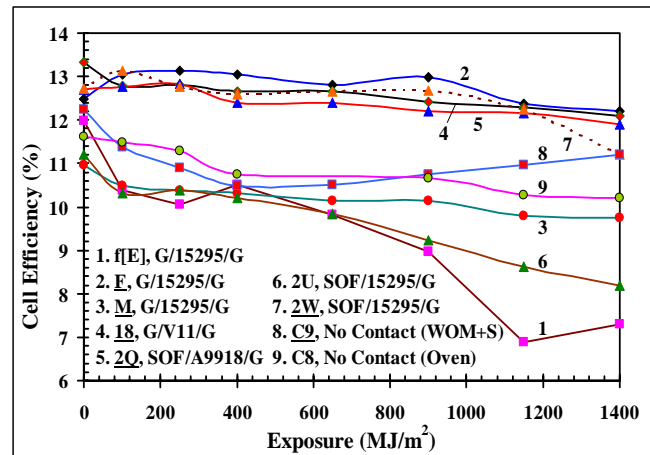


Fig. 1. Cell efficiency as a function of exposure in WOM.

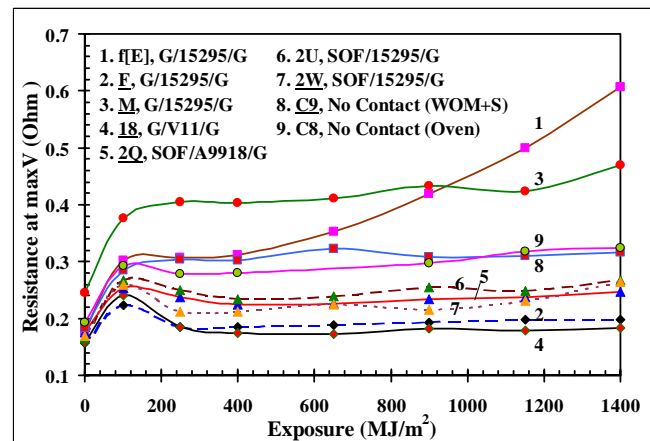


Fig. 2. R at maxV (~R_s) as a function of exposure in WOM.

4. Conclusion

Significant loss of efficiency correlated to cyclic WOM conditions; trends of increasing series resistance; and the observations of corrosion, where substantial moisture ingress was present, indicate that moisture-ingress can deleteriously affect metalization/contacts for these c-Si cells, leading to deteriorating performance and reliability.

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